FINAL TECHNICAL REPORT: Award Number 08HQGR0014 Slow or fast fault slip: the role of thermal pressurization, friction, and dilatancy

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Abstract

As faults in the earth slip, frictional heat is generated. It has long been known that the temperature anomaly near the San Andreas fault is much less than predicted based on standard estimates of frictional properties. One mechanism to explain this is that faults become very weak during earthquakes, drastically diminishing the frictional heat production. The pores of fault zone rocks are known to be saturated with aqueous fluids, and the thermal expansivity of these fluids is much greater than that of rock that hosts them. Thus as frictional heat is generated the pressure of these pore-fluids will increase, thereby reducing the frictional resistance to further slip. We have developed numerical methods for simulating this thermal pressurization process, including the coupling between quasi-static elasticity, rate and state dependent friction, and thermal and pore-fluid transport, assuming a zero-width shearing zone and neglecting transport parallel to the fault. We find that thermal pressurization becomes important much earlier in the nucleation of crustal earthquakes than was commonly believed. Specifically, we find that thermal pressurization dominates frictional weakening at slip speeds well below seismic radiation, depending strongly on hydraulic diffusivity of the surrounding rocks. Our simulations show that with the aging form of state evolution, nucleation zones tend to contract during thermal weakening, which means that detecting precursory strain will be more difficult than previously thought. Including the effects of normal stress variation on frictional state prevents the actively slipping zone from shrinking to a singularity. With the slip law form of state evolution thermal pressurization becomes dominant later in the nucleation process, but is still important late in the quasi-static nucleation process.

1 Introduction

Over the last few decades, the development of rate- and state-dependent friction laws has provided compelling models of earthquake nucleation. Concurrently, many researchers have considered thermal weakening mechanisms, including shear heating-induced thermal pressurization during rapid fault slip. The discovery of slow-slip events raised additional questions about processes that control the rate of localized fault slip. We have been exploring the mechanics of dilatant strengthening coupled to rate and state friction as a possible explanation for slow slip events. In this project, we studied earthquake nucleation as it transitions from frictionally-dominated to thermal weakening-dominated, as well as the the role of dilatant strengthening in controlling whether nucleation becomes seismic or remains a slow-slip event.

To address our project goals, we have developed finite-difference codes that solve the coupled problems for 2D elastic, diffusive systems with a 1D fault. Our original goal was to incorporate both thermal pressurization and dilatant strengthening in one synoptic model, but first to examine the mechanics of each effect in isolation. In the course of our research, we have observed interesting behavior that has motivated more careful study of these effects on their own. With thermal pressurization, in particular, we have demonstrated that it typically becomes the dominant process during earthquake nucleation, well before seismic slip has occurred. We obtained the surprising result that thermal pressurization significantly reduces the length of the nucleation zone relative to that found with rate and state friction alone.

2 Governing equations

We model the slip zone in a simplified manner by treating the principal shear zone as having zero width (that is, slip on a planar surface). Diffusion times across the low permeability fault core are much greater than earthquake nucleation times, so we treat the off-fault diffusive material as a homogeneous medium with low permeability. We also assume that diffusion of heat and pore pressure occurs only in the fault-normal direction. Slip on the fault is governed by rate- and state-dependent friction. For a detailed explanation of the governing equations, see *Segall & Rice* [2006]. The effective stress is $\sigma_{\text{eff}} = \sigma - p$.

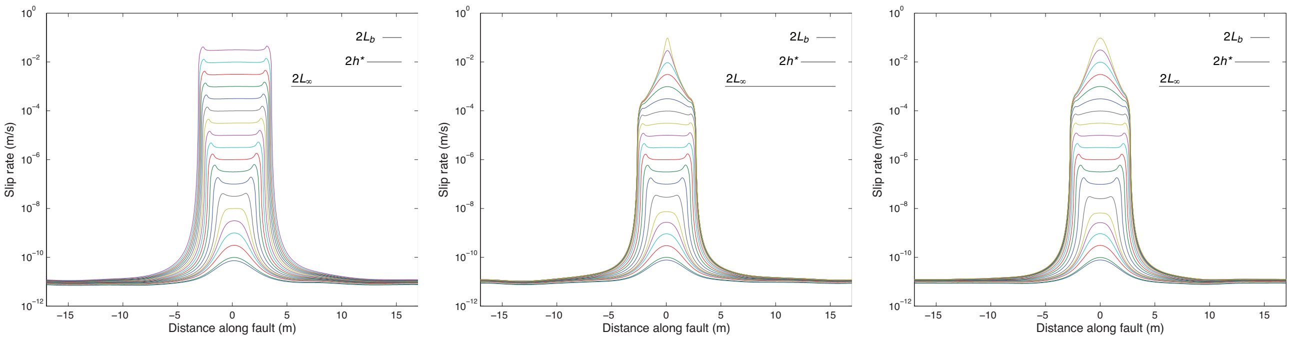

Figure 1: Results from aging law simulations in the isothermal (left) and thermal pressurization (right) cases. In these simulations, $a/b = 0.8$, $d_c = 100$ µm, $\alpha = \mu_0 = 0.6$, and $(\sigma - p_0) = 140$ MPa. Lines represent snapshots taken at times corresponding to half-decade increases in maximum slip speed $v_{\max}$ from $10^{-9.5}$ m/s to 10^{-1} m/s. **(a)** Snapshots of slip speed for isothermal, drained, aging-law nucleation. Scale bars show L_b [*Dieterich*, 1992], $h^* = Gd_c/(b-a)\sigma_{\text{eff}}$, and L_∞ [*Ampuero & Rubin*, 2008]. **(b)** Snapshots of slip speed with thermal pressurization. Comparing to (a), note that at early times (low slip speeds) the profiles are similar to the isothermal simulation. At $\sim 10^{-5}$ m/s, the profiles start to diverge. By $\sim 10^{-4}$ m/s, the profiles have distinctly different forms. The sharp peak at higher slip speeds indicates how slip is evolving toward a singularity of high slip-rate over a vanishingly short length. **(c)** Snapshots of slip speed with thermal pressurization and the *Linker & Dieterich* [1992] effect with $\alpha = \mu_0 = 0.6$. The inclusion of this effect prevents the development of a slip singularity.

$$\text{Friction:} \quad \tau_{\text{fric}} = \mu\sigma_{\text{eff}} = \left[\mu_0 + a\ln\frac{v}{v_0} + b\ln\frac{\theta v_0}{d_c}\right]\sigma_{\text{eff}} \tag{1}$$

$$\text{“Aging” state evolution law:} \quad \frac{d\theta}{dt} = 1 - \frac{\theta v}{d_c} \tag{2}$$

$$\text{“Slip” state evolution law:} \quad \frac{d\theta}{dt} = -\frac{\theta v}{d_c}\ln\frac{\theta v}{d_c} \tag{3}$$

$$\text{Normal stress effect on state:} \quad \frac{d\theta}{dt} = \begin{bmatrix}\text{state evolution}\\ \text{law (2) or (3)}\end{bmatrix} - \frac{\alpha\theta}{b\sigma_{\text{eff}}}\frac{d\sigma_{\text{eff}}}{dt} \tag{4}$$

$$\text{Shear heating (zero-width shear zone):} \quad \frac{\partial T}{\partial t} - c_{th}\frac{\partial^2 T}{\partial y^2} = 0 \tag{5}$$

$$\left.\frac{\partial T}{\partial y}\right|_{y=0} = -\frac{\tau v}{2\rho c_v c_{\text{th}}} \tag{6}$$

$$\text{Thermal pressurization (zero-width zone only):} \quad \Delta p(y=0) = \frac{\Lambda}{1+\sqrt{c_{\text{hyd}}/c_{\text{th}}}}\Delta T(y=0) \tag{7}$$

$$\text{Thermal pressurization factor:} \quad \Lambda = \frac{\lambda_f - \lambda_\phi}{\beta_f + \beta_\phi} \tag{8}$$

Note that for a zero-width shear zone and uniform thermal and hydraulic diffusivities (c_{th} and c_{hyd}), *Rice* [2006] has shown that the change in pore-pressure on the fault is proportional to the temperature change on the fault, as in equation (7). Thus, for this system we require only one finite difference grid in the numerical calculations.

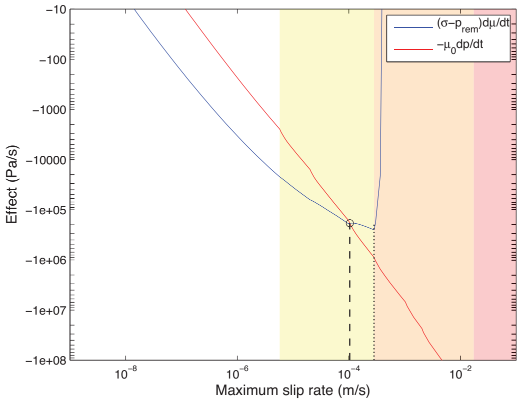

Figure 2: Weakening rates at the fastest-slipping point in the fault for time-dependent friction and pore pressure, as decomposed in the text. Critical velocity v_{crit} is shown with vertical dashed lines and is defined when $-\mu_0 dp/dt > (\sigma - p_0)d\mu/dt$. The shaded regions indicate the validity of the planar shear zone approximation. Yellow signifies $\Delta y \leq 100h$, orange signifies $\Delta y \leq 10h$, and red signifies $\Delta y \leq h$. The planar shear zone assumption used here is valid only for $\Delta y \gg h$, and a reasonable estimate is $h \approx 100$ µm.

3 Results

We have performed simulations of earthquake nucleation with thermal pressurization using a wide range of material properties and both of the state evolution laws (2) and (3). Within the context of either state evolution law, the qualitative behavior of thermal pressurization is similar over a wide range of system parameters. Yet owing to significant differences between aging law nucleation and slip law nucleation, the influence of thermal pressurization is quite different in the two cases.

A consistent result from our work modeling thermal pressurization with the aging law is that it has the effect of preventing growth of the nucleation zone. Figure 1 shows a comparison of isothermal, drained (that is, "regular") nucleation to nucleation with thermal pressurization for the aging law. The first plot shows snapshots of slip speed for the isothermal case. The result is similar to those of *Ampuero & Rubin* [2008] in that the nucleation zone takes the form of a quasi-statically growing crack—slip speed is roughly uniform inside the growing nucleation zone, and it increases at the same rate there as it does at the crack tips. With thermal pressurization (second plot), however, such a slip speed profile only occurs briefly (if at all, in some cases). By the time a slip speed of approximately 10^{-5} m/s is attained, slip begins to localize at the center of the nucleation zone.

The visual difference in the character of the slip speed profiles in Fig. 1 hints at a "critical velocity" v_{crit} that defines the speed at which thermal pressurization dominates fault strength. We quantify v_{crit} from our simulations by comparing the magnitude of two terms in the rate of change of frictional strength $d\tau_{\text{fric}}/dt = [(\sigma - p_0)d\mu/dt] - [\mu_0 dp/dt]$, which are respectively the frictional term and the thermal pressurization term. Figure 2 shows graphically the determination of v_{crit}.

We found that the concentration of slip at the center of the nucleation zone leads to a singularity in slip speed; the middle plot of Fig. 1 shows the nucleation zone evolving toward that condition. We were able to prevent the singularity from developing by including the effect of variable normal stress on frictional state, which was identified in *Linker & Dieterich* [1992]. There, the authors conducted experiments in which rock samples were slid at constant velocity while step changes in normal stress were applied. Shear stress did not immediately take on its new value; rather, it evolved toward its new value over the characteristic slip distance d_c, which follows equation (4) above. This effect is relevant to the thermal pressurization problem because fault weakening occurs via decreasing the effective normal stress $\sigma_{\text{eff}} = \sigma - p(t)$. The third plot in Fig. 1 shows the effect of the *Linker & Dieterich* [1992] mechanism when thermal pressurization is active. In this calculation, we use $\alpha = \mu_0$, which completely regularizes the problem and prevents the development of a slip singularity. This result indicates that it is important to include the *Linker & Dietrich* [1992] effect when dynamic weakening mechanisms influence σ_{eff}.

With the slip law, the effect of thermal pressurization is much less pronounced. Figure 3 shows snapshots of slip speed for simulations with (left) and without (right) thermal pressurization, otherwise using the same parameters as those of Figs. 1 and 2. Nucleation under the slip law is pulse-like, with the fastest slipping region moving away from the region that has already slipped. Because thermal pressurization is an effective slip-dependent weakening mechanism, it is less important in controlling the dynamic weakening of the fault at the pulse tip, where the slip speed is a maximum.

The greatest uncertainty in the material properties relevant to thermal pressurization is in our knowledge of the hydraulic diffusivity. Relatively few studies have documented this parameter for fault zone materials under appropriate pressure conditions. Simulations shown here assume a value of 10^{-6} m^2/s, which is consistent with observations from the Median Tectonic Line in Japan [*Wibberley*, 2002], the Nojima Fault [*Lockner* et al., 2000], and the Punchbowl Fault [*Chester & Chester*, 1998]. To explore how thermal pressurization depends on hydraulic diffusivity, we conducted simulations using a wide range of values, shown in Fig. 4. We find that, for the aging law, thermal pressurization dominates during nucleation (that is at slip speeds less than ~ 0.1 m/s) for diffusivities up to $\sim 10^{-2}$ m^2/s, or four orders of magnitude greater than inferred for faults *in situ*. With the slip law, we find that thermal pressurization dominates rate and state friction during nucleation only if $c_{\text{hyd}} \lesssim 10^{-4}$ m^2/s.

All of our work thus far has made use of the planar shear zone approximation, which is valid for times that are much greater than the diffusion time across a shear zone of width h. However, we have identified that the planar shear zone approximation is not valid at speeds greater than roughly v_{crit}. At such speeds, the heat production is sufficiently large that the simulations must take small time steps to maintain accuracy, and these time steps are no longer much greater than a realistic diffusion time across a shear zone. The color coding in Figure 2 attempts to qualitatively evaluate the validity of the planar shear zone approximation. To address this issue, future work must include a finite-width shear zone. In a finite shear zone, we expect the thermal pressurization effect to be somewhat diminished because the heat sources are distributed, which would cause the peak pressurization on the fault to be lower. This alone may act to somewhat mitigate the contraction of the rapidly slipping region.

We have demonstrated that, for nucleation with the aging law, thermal pressurization strongly restricts the growth of the nucleation zone. A major consequence is that it will be extremely challenging to detect precursory strain associated with a developing nucleation zone, which was a possibility mentioned by *Ampuero & Rubin* [2008] for aging law nucleation with a/b near 1. While the immediate prospect of application of this work to earthquake hazard mitigation is somewhat discouraging, this work will be of use to researchers who model dynamic rupture, since it givea insight into the initial heat and pore fluid conditions for such models. Additionally, this work is relevant to the related question of the mechanics of slow slip. We have suggested that whether slip is ultimately dynamic or slow depends on whether dilatancy can stabilize slip at rates below where thermal pressurization becomes dominant.

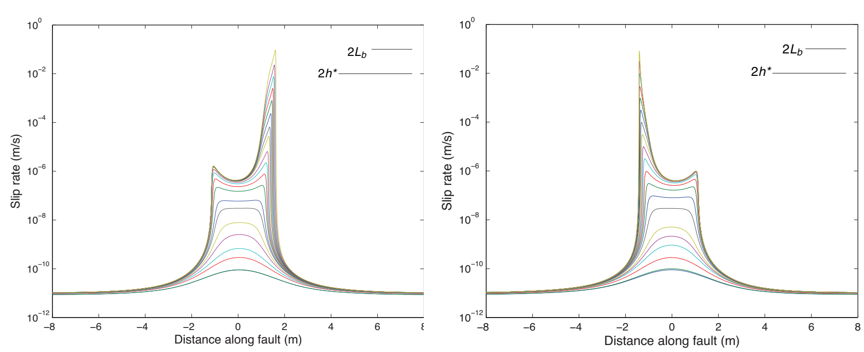

Figure 3: Nucleation with the slip law for state evolution. Left: no thermal pressurization. Right: Thermal pressurization present. The direction of slip law nucleation pulse propagation is random; these two simulations happened to result in opposite propagation directions.

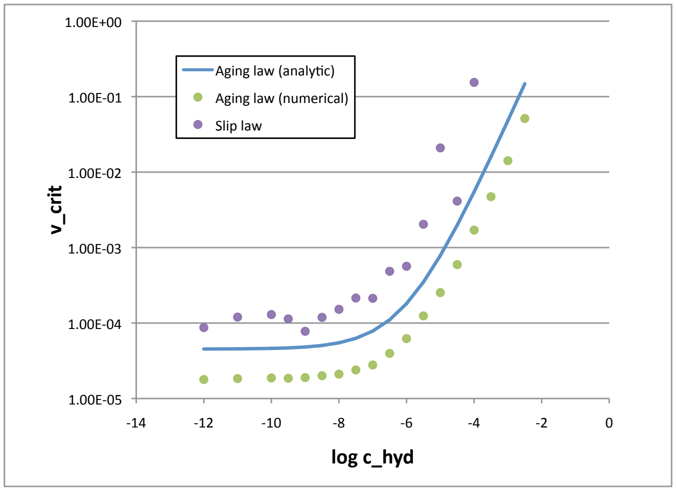

Figure 4: Critical velocity v_{crit} as a function of hydraulic diffusivity c_{hyd}. An analytic estimate for a spring-slider system with aging law friction [*Segall & Rice* 2006] is shown.

We are in the process of preparing a manuscript to be submitted to the Journal of Geophysical Research describing these results in more detail *Schmitt, Segall, and Matsuzawa, in prep.* Publications Resulting from current funding are listed in **bold** below.

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